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ORIGINAL RESEARCH ARTICLE

Comparative Analysis of Blowing Agents for Coal Gasification in Oxy-Fuel Energy Complexes

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ABSTRACT

Oxy-fuel energy complexes (OFCs) offer a promising approach for carbon dioxide (CO_2) capture in coal-fired power plants, but efficient coal gasification is crucial to maintain high cycle efficiency. However, there are currently no studies on the effect of the type of blowing agent on OFCs' efficiency. This study evaluates various blowing agents—air, oxygen, steam, CO_2, and their mixtures—for gasification of Kaakhemsky coal, focusing on optimal consumption, generator gas composition, temperature, calorific value, and efficiency. Using heat balance equations and equilibrium constants, calculations were performed under assumptions of stationary operation at 40 atm pressure, incorporating reactions like water-gas shift and methane reforming. Results indicate that air-based blasting yields high nitrogen content (up to 54%), leading to low calorific values (8.4 MJ/m³) and high NOx emissions, rendering it unsuitable. Pure CO_2 and steam blasting require excessive agent consumption (6.2–10 kg/kg coal) and external heat, producing low-quality gas with high CO_2 or H_2O fractions inhibiting combustion. Oxygen blasting provides high-quality gas (2% non-combustibles, 17.8 MJ/m³ calorific value) but demands pure oxygen and excess heat recovery at 1004°C. Mixtures of oxygen with steam or CO_2 emerge as optimal: oxygen-steam reduces oxygen consumption to 0.3 kg/kg coal, enhancing calorific value to 19.7 MJ/m³ at 187°C, while oxygen-CO_2 achieves 17.2 MJ/m³ at 260°C without steam generation needed. Both options minimize non-combustible species fraction (<7%), support stable combustion, and align with OFCs' requirements for low emissions and high efficiency. Recommendations include cycle modeling to compare these for integrated power plant design, potentially improving CO_2 capture and thermal performance.

Keywords: Oxy-fuel combustion; Coal gasification; Blasting agents; Allam cycle; Thermal efficiency; CO_2 capture; Syngas composition; Heat recovery

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1. Introduction

Oxy-fuel combustion has emerged as a promising technology for mitigating carbon dioxide (CO_2) emissions from power generation, particularly in the context of global warming driven by anthropogenic greenhouse gases. As highlighted by the Intergovernmental Panel on Climate Change (IPCC) reports [1, 2], CO_2 levels have risen by approximately 2.5 ppm annually over the past decade, with the power energy sector contributing about 25% of global emissions [3, 4]. Oxy-fuel combustion, which is essentially fuel combustion in a nearly pure oxygen environment to produce CO_2-rich flue gas for easy CO_2-capture and storage, offers a viable pathway for reducing greenhouse gas emissions compared to conventional air-fired systems [5-7]. This technology is especially relevant for coal-based power plants, given coal's abundance and its high share in power generation worldwide. The Allam cycle, a semi-closed Brayton regenerative cycle using supercritical CO_2 as the working fluid, represents a cornerstone in oxy-fuel power systems. Developed by Allam et al. [8,9], it achieves high efficiencies (up to 50%) through high turbine inlet temperatures (1000–1200°C) and pressures (20–40 MPa), facilitated by high heat regeneration from turbine exhaust gases and air separation unit (ASU) waste heat. Thermodynamic analyses of natural gas-fired Allam cycles have been extensively documented. For instance, Scaccabarozzi et al. [10] reported a 54.8% efficiency at 1123°C inlet temperature and 283.62 bar inlet pressure, while Hanak et al. [11] optimized parameters to reach 56.5% efficiency at 30 MPa and 1083°C at the turbine inlet, emphasizing the role of multi-flow regenerators and ASU modeling in performance assessments. However, coal resources are three times more abundant than natural gas [12,13], prompting research into coal-integrated Allam cycles.

There are numerous studies devoted to the thermodynamic optimization and development of coal-fired Allam cycle designs [14–19], with cycle efficiencies typically not exceeding 43%. Almost all of them utilize oxygen-steam blowing for coal gasification, assuming it to be the most suitable for the Allam cycle. However, using carbon dioxide as a blowing agent may be more suitable, since CO_2 is a byproduct of the cycle and does not need to be generated. Furthermore, the paper [20] demonstrates that using the carbon dioxide-steam blowing at a high temperature of about 600°C (turbine exhaust) can have an unexpected positive effect on cycle efficiency. The achieved efficiency was 47%, which is significantly higher than that achieved in cycles with oxygen-steam blowing (no more than 43%). Thus, the choice of blowing agent for gasification can have a significant impact on the efficiency of the coal-fired Allam cycle. However, a comparative study on the effect of different blowing agents on the efficiency of the coal-fired Allam cycle has yet to be presented in the literature.

This paper aims to close this gap. The effect of different gasifying agents—air, oxygen, steam, CO_2, and their mixtures—for the gasification of Kaakhemsky coal, emphasizing optimal agent consumption, generator gas composition, temperature, calorific value, and process efficiency, was investigated. The obtained results will be used to study the influence of a blowing agent used on the efficiency of the coal-fired Allam cycle.

2. Methodology & Calculation

In this work, the following gasification blowing agents were considered: air, oxygen and water vapor (H_2O). The use of the mathematical model proposed in [21] encountered difficulties when investigating CO_2 as a blowing agent, so in this paper the study of pure carbon dioxide for gasification had to be abandoned. Oxygen purity was assumed to be 95.6%, and air was understood as a mixture of 21% oxygen and 79% nitrogen. The air temperature at the inlet of a gasifier was assumed to be 20°C, the oxygen temperature was 30°C, and the steam temperature was 300°C. When mixing carbon dioxide with other blasting agents, two cases were considered: cold carbon dioxide with a temperature of 40°C (at the outlet of the water separator-cooler of the Allam cycle) and preheated hot carbon dioxide with a temperature of 300 °C.

The composition of the generator gas obtained from coal by gasification was calculated using the method described in [21]. Some changes were made to the method during the calculation. First, the consumption of blowing agents was specified not using the oxidizer excess coefficient α, but using the relative mass consumption of the blowing agent for coal gasification (kg agent/kg coal). Second, in addition to the reactions of water gas ($H_2O + CO \leftrightarrow CO_2 + H_2$) and steam methane reforming ($CH_4 + H_2O \leftrightarrow CO + 3H_2$), the reaction of carbon dioxide methane reforming ($CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$) was also taken into account.

The calculation of the temperature of the generator gas was carried out iteratively using the heat balance equation of the gasifier (1):

$$Q_{\mathrm{chem}_{coal}}+Q_{phys_{coal}}+Q_{phys_{agent}}=Q_{\mathrm{chem}_{gas}}+Q_{phys_{gas}}+Q_{evp}+Q_{a\mathrm{sh}}+Q_{env}, \quad (1)$$

where $Q_{\mathrm{chem}_{coal}}$ is the calorific value (chemical heat) of gasified coal;

$Q_{phys_{coal}}$ – physical heat of coal;

$Q_{phys_{agent}}$ – physical heat of the blowing agent;

$Q_{chem_{gas}}$ – calorific value (chemical heat) of generator gas;

$Q_{phys_{gas}}$ – physical heat of generator gas;

Q_{evp} – heat spent on evaporation of water contained in coal;

Q_{ash} – heat of ash residue;

Q_{env} – heat loss to the environment.

Kaakhemsky coal grade G (gaseous) was chosen as the gasified fuel; its composition by working mass and combustion heat are given in Table 1.

Table 1. Composition of Kaakhemsky coal grade G by working mass and heat of combustion according to [22]

Parameter	Meaning
Humidity of the working mass, %	5
Ash content of the working mass, %	14.3
Sulfur content per working mass, %	0.4
Carbon content per working mass, %	65
Hydrogen content per working mass, %	4.8
Nitrogen content per working mass, %	1
Oxygen content per working mass, %	9.5
Heat of combustion, kJ/kg	25410

Kaakhemsky coal grade G was chosen for the study of the influence of the blasting agent on gasification for the following reasons:

1) High calorific value;

2) High content of carbon and hydrogen – the main sources of heat;

3) Low ash and moisture content, which reduces heat loss with ash during gasification and heat loss due to water evaporation;

4) High oxygen content, which allows to reduce oxygen consumption for gasification (if the blowing agent is air or oxygen) and to reduce the costs of producing pure oxygen in ASU.

The physical heat of coal was calculated using the following formula (2):

$$Q_{phys_{coal}}=\left(C_{dry}\cdot\left(1-\frac{W_p}{100}\right)+C_{H2O}\cdot\left(1+\frac{W_p}{100}\right)\right)\cdot t_{coal} \quad (2)$$

where W_p is the moisture content of coal per working mass, %;

C_{dry} and C_{H2O} – heat capacity of dry mass of coal and moisture in coal, $\frac{kJ}{kg\cdot K}$;

t_{coal} – coal temperature before gasification, °C. Taken as 20 °C.

The physical heat of the blowing agent was calculated using formula (3):

$$Q_{phys_{agent}}=\left(V_{N_2}\cdot C_{N_2}+V_{O_2}\cdot C_{O_2}\right)\cdot t_{nom}+V_{steam}\cdot C_{steam}\cdot t_{steam}+V_{CO_2}\cdot C_{CO_2}\cdot t_{CO_2}, \quad (3)$$

where V_{N2}, V_{O2}, V_{steam} and V_{CO2} are the specific consumption rates of nitrogen, oxygen, steam and carbon dioxide, respectively, m^3 /kg of coal;

C_{N2}, C_{O2}, C_{steam} and C_{CO2} are the specific heat capacities of nitrogen, oxygen, steam and carbon dioxide $\frac{kJ}{m^3\cdot K}$;

T_{nom}, t_{steam}, t_{CO2} – temperatures of the nitrogen-oxygen mixture (nom), steam and carbon dioxide, respectively, °C.

The physical heat of the generator gas was calculated based on the composition of the generator gas, similar to coal. Heat loss to the environment during gasification was assumed to be 5% of the calorific value of the generator gas. Heat loss with ash was calculated using formula (4):

$$Q_{ash}=C_{ash}\cdot\frac{A_p}{100}\cdot t_{gas}, \quad (4)$$

where C_{ash} is the specific heat capacity of ash, $\frac{kJ}{kg\cdot°C}$. It was determined by the temperature of the generator gas according to [2];

A_p – ash content in the working mass of coal;

t_{gas} – temperature of generator gas, specified in approximation, °C.

The following assumptions were made during the calculation:

- the gasifier operates continuously in a stationary mode;
- the pressure in the gas generator is constant and equal to 40 atm (corresponds to Shell gasifiers);
- ash and the produced generator gas leave the gasifier together, ash removal is carried out afterwards;
- the calculation of heat balance equations is carried out using the equilibrium constants of the main chemical reactions;
- the resulting generator gas consists of CO_2, CO, H_2O, H_2, N_2, CH_4 and SO_2.
- The chemical and thermal efficiency of the gasification were calculated using formulas (5) and (6):

$$\eta_{chem}=\frac{Q_{chem_{gas}}}{Q_{chem_{coal}}}, \quad (5)$$

$$\eta_{thermal}=\frac{Q_{chem_{gas}}+Q_{phys_{gas}}}{Q_{chem_{coal}}+Q_{phys_{coal}}+Q_{phys_{agent}}}. \quad (6)$$

3. Result & Discussion

Table 2 shows the results of calculating the optimal consumption rate for each blowing agent, the composition of the resulting generator gas, the temperature of the generator gas, the calorific value (chemical heat) of the generator gas, and the chemical and thermal efficiencies of gasification.

Table 2. Results of gasification calculation depending on the type of blowing agent

Blowing agent	Optimum consumption rate, kg/kg coal				
	Air	Oxygen	Steam	Carbon dioxide	Total
Air	2.3	-	-	-	2.3
Air + steam	0.8	-	0.45	-	1.25
Air + carbon dioxide (40 °C)	1.8	-	-	0.8	2.6
Air + carbon dioxide (300 °C)	1.8	-	-	0.4	2.2
Oxygen	-	0.52	-	-	0.52
Oxygen + steam (300 °C)	-	0.3	0.2	-	0.5
Oxygen + carbon dioxide (40 °C)	-	0.42	-	0.3	0.72

Blowing agent	Optimum consumption rate, kg/kg coal				
	Air	Oxygen	Steam	Carbon dioxide	Total
Oxygen + carbon dioxide (300 °C)	-	0.41	-	0.3	0.71
Steam	-	-	2.3	-	2.3
Steam + carbon dioxide (40 °C)	-	-	2.3	0.5	2.8
Steam + carbon dioxide (300 °C)	-	-	2	0.2	2.2

Blowing agent	Composition of generator gas, %						
	CO_2	CO	H_2O	H_2	N_2	CH_4	SO_2
Air	0.7	34.2	-	0.2	53.6	11.2	0.1
Air + steam	21.8	15.3	-	-	29	33.8	0.2
Air + carbon dioxide (40 °C)	9.7	38.7	-	-	40.5	10.9	0.1
Air + carbon dioxide (300 °C)	2.5	41.8	-	-	43.8	11.8	0.1
Oxygen	-	73.6	-	0.5	2	23.6	0.2
Oxygen + steam (300 °C)	5.5	58.6	-	-	1.4	34.2	0.2
Oxygen + carbon dioxide (40 °C)	1.1	75.7	-	-	1.6	21.4	0.2
Oxygen + carbon dioxide (300 °C)	0.1	76.7	-	-	1.5	21.4	0.2
Steam	15.5	-	62.5	-	0.2	21.7	0.1
Steam + carbon dioxide (40 °C)	21.6	-	58	-	0.2	20.1	0.1
Steam + carbon dioxide (300 °C)	20.3	-	55.7	-	0.3	23.7	0.1

Blowing agent	Generator gas temperature, °C	Calorific value		Gasification efficiency	
		MJ/kg	MJ/m^3	Chemical	Thermal
Air	638	22	8.4	0.85	0.943
Air + steam	269	24	14	0.927	0.945
Air + carbon dioxide (40 °C)	138	24	8.8	0.928	0.945
Air + carbon dioxide (300 °C)	175	24	9.5	0.928	0.945
Oxygen	1004	22.2	17.8	0.859	0.941
Oxygen + steam (300 °C)	187	24.2	19.7	0.937	0.945
Oxygen + carbon dioxide (40 °C)	263	24	17.2	0.926	0.945
Oxygen + carbon dioxide (300 °C)	218	24.1	17.4	0.933	0.945
Steam	89	25.3	7.8	0.98	0.948
Steam + carbon dioxide (40 °C)	85	25.3	7.2	0.98	0.948
Steam + carbon dioxide (300 °C)	72	25.3	8.5	0.98	0.948

Figure 1 shows a histogram on optimum consumption rates of different blowing agents depending on the type of blowing.

For a number of reasons, it is recommended to use a type of blowing that ensures minimal blowing agent consumption. First, many blowing agents (air, steam, carbon dioxide, and their mixtures) contain non-combustible species (N_2, H_2O, CO_2, respectively), their presence reduces the calorific value. Second, the presence of non-combustible species also complicates the fuel combustion process, as the gas becomes more difficult to ignite and maintain stable combustion. Third, high blowing agent consumption rate increases the costs of its generation (steam, pure oxygen) or pretreatment (carbon dioxide heating), which reduces cycle net efficiency. And finally, increasing the blowing agent consumption also increases the consumption of generator gas, which increases the cost of its compression and, accordingly, further reduces cycle net efficiency.

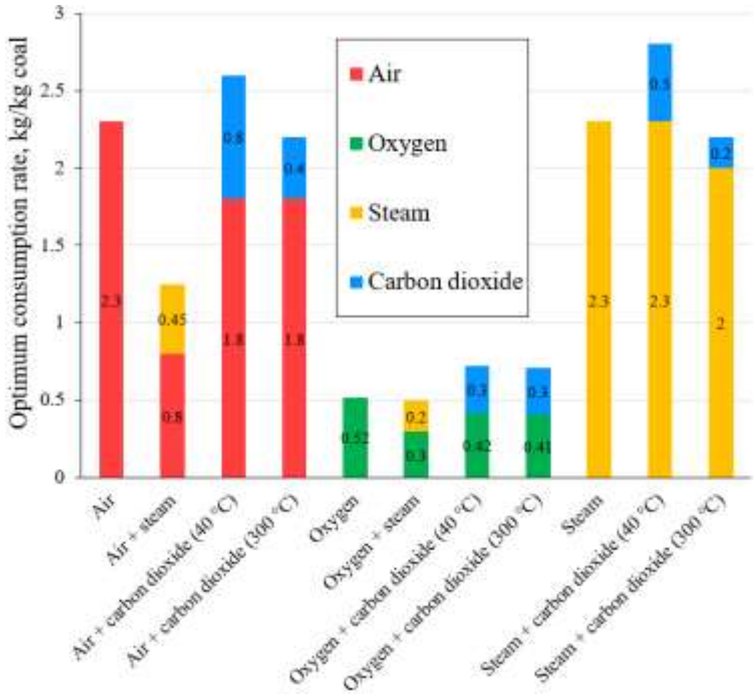

Figure 1. Optimum consumption rates for different blowing agents

As Figure 1 shows the least amount of blowing agent is required for gasification with pure oxygen and oxygen mixed with steam and carbon dioxide – 0.5–0.72 kg/kg coal. This is due to the low fraction of reaction-inhibiting non-combustible species and the high fraction of the oxidizer (oxygen) in a blowing agent, which intensifies gasification. At the same time, other blowing methods require much higher consumption – 1.25–2.8 kg of blowing agent per 1 kg of coal, which caused by a high fraction of non-combustibles. It can be concluded that the lowest gasification costs and the highest quality of generator gas should be observed with gasification with pure oxygen and oxygen mixed with steam and carbon dioxide.

The histogram on the composition of the generator gas for different blowing agents is shown in Figure 2.

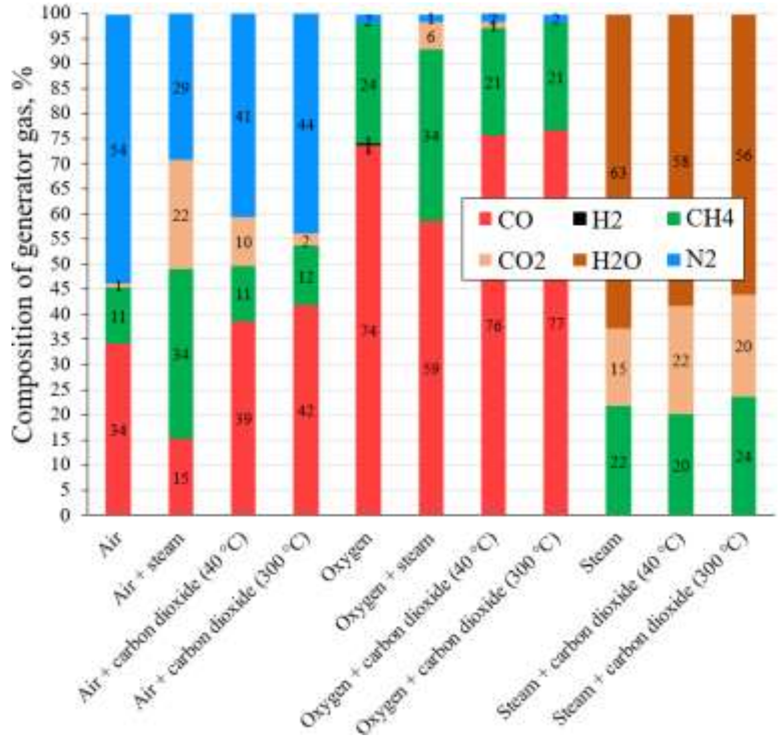

Figure 2. Composition of generator gas depending on the type of blowing agent at its optimal consumption

As expected from the consumption rates of blowing agents, the highest quality of generator gas is ensured by blowing with pure oxygen (only 2% non-combustible species: CO_2, H_2O, N_2, SO_2) and a mixture of pure oxygen with steam (7%) and carbon dioxide (2-3%) since those blowing agents contain almost no non-combustibles. When using other blowing agents, with high fraction on non-combustibles, the quality of generator gas decreases sharply: the fraction of non-combustible species in the resulting generator gas is at least 46% (air + hot carbon dioxide) and reaches up to 80% (steam + cold carbon dioxide). A high concentration of non-combustible species reduces the calorific value; increases the consumption of generator gas and the cost of its compression; inhibits the combustion process and complicates fuel ignition. These problems are least common for blowing with pure oxygen and oxygen mixed with steam and carbon dioxide, since such generator gas contains the smallest amount of non-combustibles (no more than 7%).

The mass and volumetric calorific values of the generator gas depending on the type of blowing are shown in Figure 3.

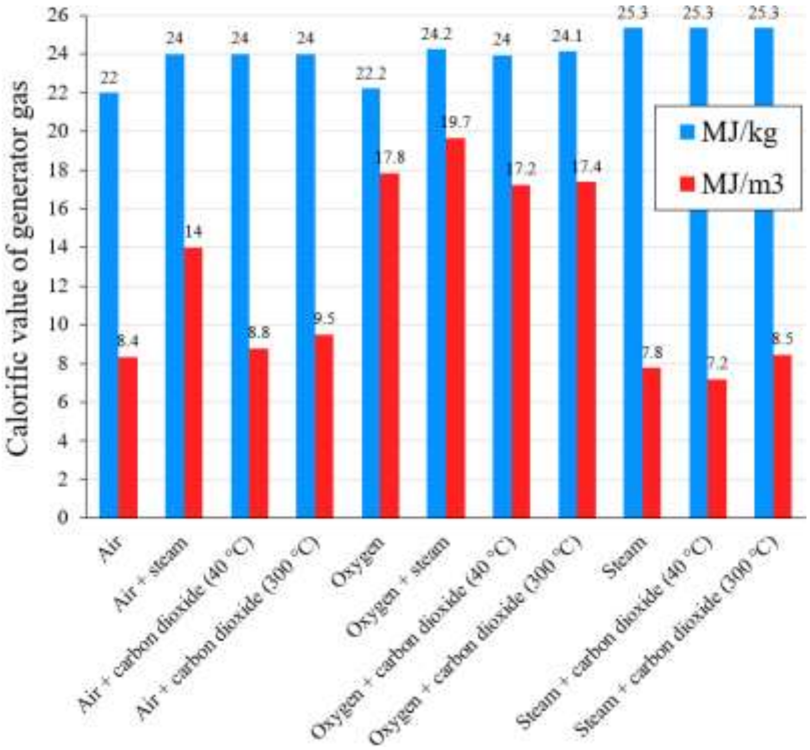

Figure 3. Calorific value of generator gas depending on the type of blowing agent at its optimal consumption

As can be seen from Figure 3, the mass calorific values for most types of blowing do not vary significantly: 22–25.3 MJ/kg. Gasification with pure steam and steam mixed with carbon dioxide shows the highest calorific value per mass: 25.3 MJ/kg, which is only slightly less than that of coal (25.4 MJ/kg). However, when converted to volume, the calorific value is low, although higher than when using carbon dioxide: 7.2–8.5 MJ/m^3. The low volumetric value is caused by low concentration of combustible species (CO, H_2, CH_4) in the generator gas. At the same time, the mass calorific value is very high because of the low density of the gas obtained since it contains of no less than 56% H_2O which are light species. The use of air for gasification also makes it possible to achieve a high calorific value per mass: 22 MJ/kg, but, when converted to volume, the calorific value decreases significantly, becoming the same as when using steam: 8.4 MJ/m^3. The mass calorific value is lower than under steam-carbon dioxide gasification since nitrogen has much higher density than H_2O (0.32 kg/m^3 H_2O and 0.87 kg/m^3 N_2 under 1 atm and 300 °C). The fraction of combustible species increases up to 2 times compared to steam blowing (45% against 22%), but the combustibles are mostly CO with much lesser calorific value (12.6 MJ/m^3) than CH_4 (35.8 MJ/m^3) under steam gasification. Mixing both carbon dioxide and steam with air makes it possible to significantly increase the calorific value: up to 24 MJ/kg or up to 14 MJ/m^3. Adding steam shifts the steam reforming reaction ($CH_4 + H_2O = CO + 3 H_2$) towards the formation of methane instead of CO, which increases both the volumetric and mass calorific values since CH_4 is light species (0.34 kg/m^3 under 1 atm and 300 °C). When using pure oxygen as a blowing agent, the mass calorific value decreases significantly: to 22.2 MJ/kg, but the volumetric calorific value increases to 17.2 MJ/kg. The latter is due to the high concentration of combustible species (97%). However, most of them (74%) are CO, which is relatively heavy species (1.15 kg/m^3). This reduces the mass calorific value. Mixing steam with oxygen allows for a significant increase in both the mass (up to 24.2 MJ/kg) and volumetric (up to 19.7 MJ/m^3) calorific values. This is due to the higher proportion of CH_4 in the gas (34% against 24%), which is caused by the shift of the methane steam conversion reaction towards methane, which is lighter and has a higher calorific value than CO. Mixing carbon dioxide with oxygen instead of steam also increases the mass calorific value (up to 24.1 MJ/kg), but the volumetric calorific value remains almost unchanged (17.4 MJ/m^3). This is due to the fact that the total fraction of combustible species (97%) and the CO/CH_4 ratio in them (76/21) remained almost unchanged compared to oxygen gasification. Therefore, the highest volumetric calorific value is provided by blowing with a mixture of pure oxygen and steam. This is due to the overall high fraction of combustible species (93%) and the particularly high fraction of methane (34%).

The histogram of chemical and thermal efficiency of gasification for different blowing agents is shown in Figure 4.

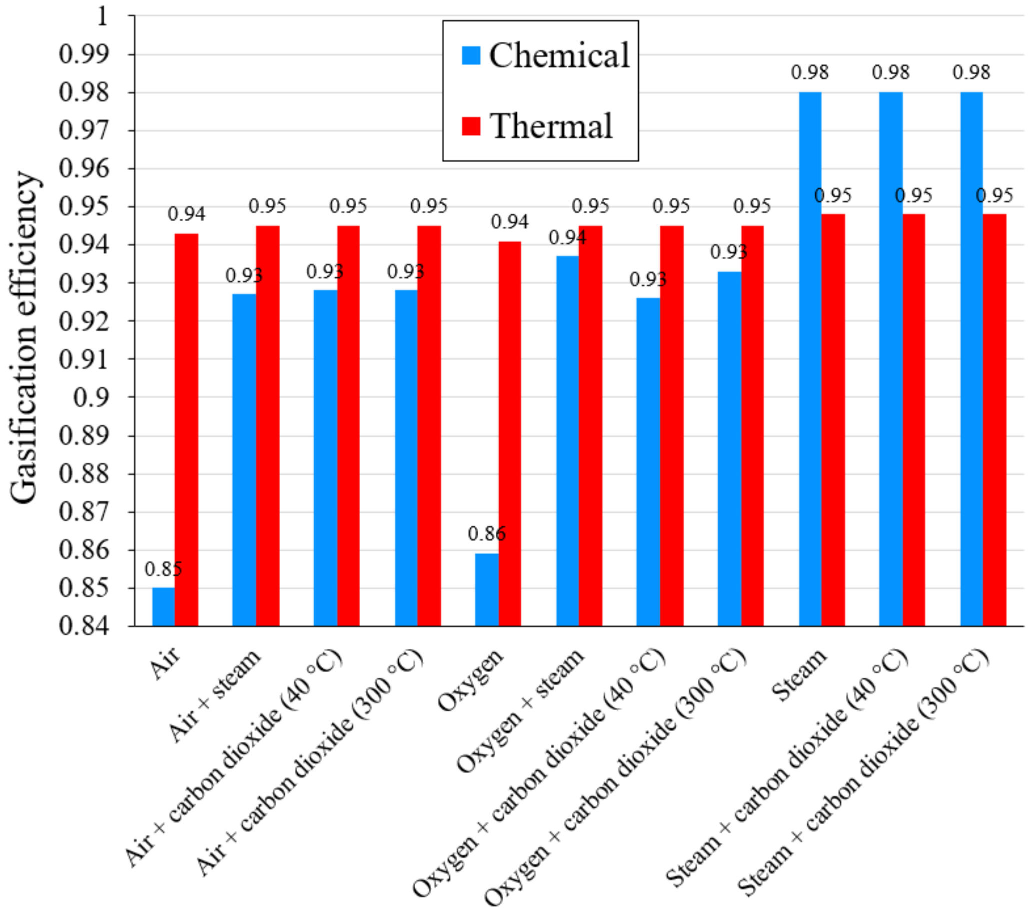

Figure 4. Gasification efficiency depending on the type of blowing agent at its optimal consumption

As Figure 4 shows, the thermal efficiency changes insignificantly and ranges from 0.94 to 0.95, regardless of the type of blowing. This is due to the fact that during gasification, heat is lost mainly to the environment, while other heat losses (with ash, for water evaporation) are small compared to the environmental ones. However, the chemical efficiency varies significantly depending on the blowing agent: the lowest efficiency 0.85 is achieved with air gasification. With oxygen gasification, the efficiency increases up to 0.86. Mixing either steam or carbon dioxide with air or oxygen increases the chemical efficiency up to 0.93. When using pure steam, the chemical efficiency is 0.98; mixing carbon dioxide with steam has no effect on the efficiency. Adding H_2O increases the proportion of CH_4 in the generator gas, which increases its volumetric calorific value and reduces its density, which increases the mass calorific value and, consequently, increases chemical efficiency. At the same time, the addition of carbon dioxide increases the total fraction of the combustible species, which also increases both the volumetric and mass calorific values and, consequently, chemical efficiency. Looking at the Figure 4, it can be concluded that steam blowing provides the most efficient conversion of coal heat into generator gas heat.

It's noteworthy that if the chemical efficiency varies significantly while the thermal efficiency remains nearly constant, this means the generator gas temperature varies significantly between different blowing types. The chemical heat of the coal, if not lost or converted into chemical heat of the gas, should contribute to its heating. Therefore, types of blowing with low chemical efficiency are expected to produce higher generator gas temperatures. The histogram of generator gas temperatures for different blowing agents is shown in Figure 5. Our assumption turned out to be correct: oxygen and air blowing have the lowest chemical efficiency and the highest generator gas temperature.

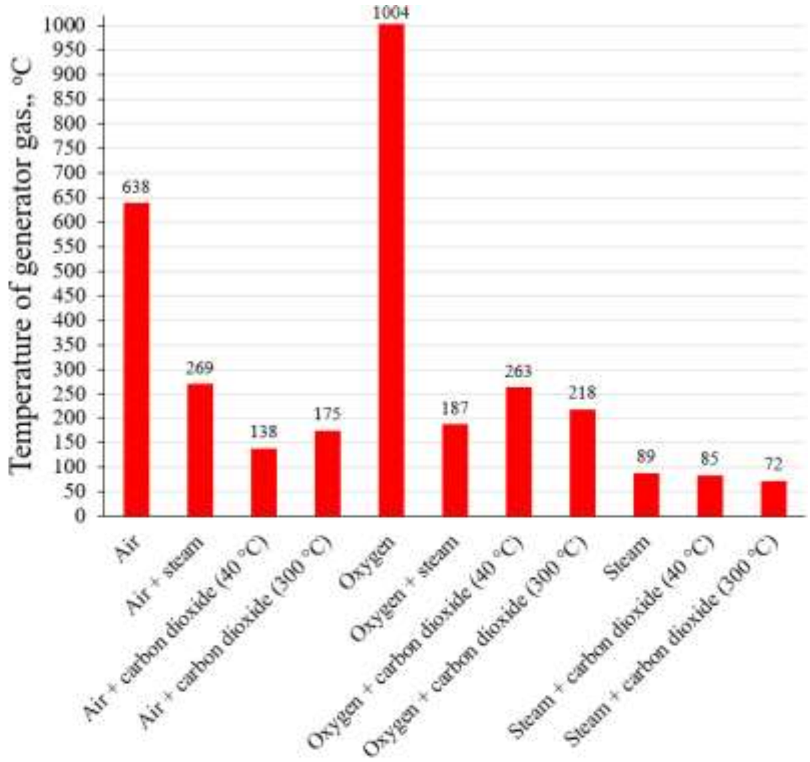

Figure 5. Temperature of generator gas depending on the type of blowing agent at its optimal consumption

High generator gas temperatures significantly increase the cost of compressing it before entering the combustion chamber, reducing cycle net efficiency. For this reason, if the generator gas temperature is high, excess heat must be recovered beforehand. This need for recovery complicates the cycle design, thereby increasing capital costs. On the other hand, recovered heat can be used to generate additional power in a secondary cycle or for heating, which increases overall cycle efficiency. Another possible use for excess generator gas heat is pre-treatment of the blowing agent, if needed: generating and superheating water vapor or preheating carbon dioxide. The question of which generator gas temperature is more advantageous—high or low—should be addressed in a separate study.

As can be seen in Figure 5, the highest generator gas temperature is achieved during gasification with pure oxygen – approximately 1000°C. Such high temperature is caused by the absence of inert species in the blowing agent as they can take away the heat released during oxidation for their own heating. Replacing pure oxygen with air reduces the gas temperature to 640 °C, since the large concentration of inert nitrogen appears in the blowing agent. The lowest generator gas temperature is achieved through gasification with steam and steam mixed with carbon dioxide – less than 100 °C. In fact, such generator gas has no excess heat and can be directly fed into a compressor. Steam and carbon dioxide also absorb some of the heat generated during gasification. But they have a much higher heat capacity than nitrogen, and a higher concentration in the blowing agent (up to 80% instead of maximum 55% for nitrogen, see Fig. 2). This results in lower gas temperatures. Mixing steam with air or oxygen achieves higher generator gas temperatures: 270°C (air + steam) or 190°C (oxygen + steam). Mixing carbon dioxide with air instead of steam reduces the temperature of the generator gas to 140°C, while mixing carbon dioxide with oxygen instead of steam increases the temperature of the generator gas to 260°C. Thus, when using mixtures of oxygen and air with steam and carbon dioxide as a blowing agent, the temperature of the generator gas is approximately 150–250°C, which is much lower than when using pure air or oxygen (640–1000ºC). This is due to an increase in the chemical efficiency from 0.85–0.86 up to 0.94, while the thermal efficiency remains almost unchanged. This means that more of the coal's calorific value is converted into the calorific value of the generator gas, and therefore less energy is used to heat it, which reduces the temperature. The heat of such generator gas can be utilized to heat network water or to generate power in a secondary power cycle. Both low-boiling working fluid cycles and steam-turbine units can be used for this.

It is noteworthy that, according to Figure 5, the temperature of the generator gas exceeds 300°C only during gasification with air and oxygen. Generator gas at this temperature could be used to preheat a blowing agent before gasification. However, gasification with air or oxygen does not require heat from external sources, while during gasification with steam or carbon dioxide, which require preheating the generator gas has a temperature below 300°C and therefore cannot be used to preheat the blowing agent. This means that, regardless of the type of blowing, the heat from the generator gas cannot be utilized for pre-treating a blowing agent.

The use of each type of blowing agent should be examined in detail. First and foremost, the use of air and it's any mixtures must be excluded, despite the fact that air is the most readily available blowing agent, requiring no pretreatment. The reason for this refusal is the high N_2 fraction in the generator gas (at least 29%, see Table 2). This inevitably causes high NO_x emissions during combustion, which is unacceptable for OFCs, one of whose primary objectives is to eliminate NO_x emissions by removing N_2 from the reaction zone.

Gasification with pure steam and its mixture with carbon dioxide should also be avoided. The first reason is the low calorific value of the generator gas, that does not exceed 8.5 MJ/m^3, which is only slightly higher than with carbon dioxide blowing. The second reason is the need for additional heat supply from external sources to generate steam and facilitate gasification. Furthermore, with steam gasification, the generator gas contains a large amount of H_2O (at least 56%), which also acts as a combustion inhibitor, although not as strong as CO_2, and complicates fuel combustion.

Finally, gasification with pure oxygen and its mixtures with steam and carbon dioxide should be considered in detail. The main advantages of oxygen gasification are the high calorific value (17.8 MJ/m^3) and the high quality of the generator gas (the fraction of non-combustible species is only 2.2%). The main disadvantage of oxygen gasification is the need to generate pure oxygen which increases the cost of the ASU and reduces the cycle net efficiency. In addition, the generator gas obtained by oxygen gasification has a very high temperature – approximately 1000 °C, which creates the need to utilize excess heat. These problems can be solved by mixing steam or carbon dioxide with oxygen. When gasifying with a mixture of oxygen and steam (at a steam temperature 300 °C), the minimum oxygen consumption rate required for stable gasification decreases from 0.52 to 0.3 kg O_2/ kg coal with a steam consumption rate 0.2 kg/kg coal. In this case, the calorific value of the generator gas increases (up to 19.7 MJ/m^3), and the temperature decreases to 190 °C, while the quality of the generator gas decreases only slightly (the fraction of non-combustible species increases from 2.2 to 7%). The main disadvantage of steam-oxygen gasification is the need to generate steam, which complicates the cycle scheme and reduces its efficiency. As an alternative, mixing carbon dioxide with oxygen can be considered. With oxygen-carbon dioxide gasification, oxygen consumption rate decreases from 0.52 to 0.42 kg/kg coal with a carbon dioxide consumption rate 0.3 kg/kg coal, while the calorific value (17.2 MJ/m^3) and the quality of the generator gas (3% non-combustible species) remain almost unchanged, while the temperature of the generator gas decreases to 260 °C. The main advantage of oxygen-carbon dioxide gasification over oxygen-steam gasification is that CO_2 does not need to be generated for gasification, as it is a byproduct of OFC. Furthermore, CO_2 utilization in the gasifier reduces CO_2 disposal costs and increases net efficiency. Preheating the carbon dioxide (up to 300°C) does not significantly affect gas parameters.

Thus, the best blowing options for coal gasification in OFCs are steam-oxygen and carbon dioxide-oxygen blowing. They provide high calorific value (17–20 MJ/m^3), high quality (no more than 7% non-combustible species), low generator gas temperature (no more than 260°C), and low blowing agent consumption (no more than 0.7 kg agent/kg coal). It is recommended to consider both blowing options in coal-gasified OFCs' schemes to accurately determine the most effective.

4. Conclusion

1. Using air as a blowing agent results in a high N_2 fraction in the generator gas (54%), which is unacceptable for oxy-fuel cycles. Furthermore, the required air consumption rate is quite high (2.3 kg/kg coal), and the resulting generator gas has a low calorific value (8.4 MJ/m^3) and a high temperature (640 °C). For these reasons, air blowing is not recommended for coal-gasification cycles.

2. Mixing steam (at 300°C) with air improves gasification quality. The required air consumption decreases to 0.8 kg/kg coal with a steam consumption of 0.45 kg/kg coal, the calorific value increases to 14 MJ/m^3, and the gas temperature decreases to 270°C. However, the N_2 fraction is still very high (29%), making steam-air blowing unsuitable for oxy-fuel coal-gasification cycles.

3. Mixing carbon dioxide with air instead of steam reduces the air consumption to 1.8 kg/kg coal with a carbon dioxide consumption of 0.8 (without preheating) or 0.4 kg/kg of coal (with preheating to 300 °C), while the generator gas temperature decreases to 140–180 °C, and the calorific value increases to 8.8–9.5 MJ/m^3. However, such generator gas still contains an unacceptably high amount of N_2 (at least 39% fraction). For this reason, air-carbon dioxide blowing is not recommended for coal-gasified OFC plants.

4. Steam gasification also requires heat supply from external sources, though not at such extent as carbon dioxide gasification. Steam consumption rate is 2.3 kg/kg coal, and the generator gas has a low temperature of approximately 90°C and, therefore, does not require pre-cooling before compression. However, its calorific value is low (7.8 MJ/m^3), and it contains 63% H_2O fraction. Furthermore, steam for gasification must be generated, which reduces the efficiency of the cycle. The addition of carbon dioxide to the steam does not significantly affect the resulting generator gas. Therefore, steam and steam-carbon dioxide gasification are not recommended for coal-gasified OFC cycles.

5. The main disadvantage of oxygen gasification is the need to generate pure oxygen, which increases the operating costs of the ASU and reduces the cycle net efficiency. Oxygen consumption rate for gasification is at least 0.52 kg/kg coal; the resulting generator gas has very high quality (only 2% non-combustible species), a high calorific value (17.8 MJ/m^3), and a very high temperature (approximately 1000°C). Prior to compression, generator gas excess heat must be recovered, which complicates the cycle design. For this reason, oxygen gasification is not recommended in OFC coal-gasified cycles.

6. The quality of gasification can be improved by mixing steam with oxygen. Oxygen consumption rate is reduced to 0.3 kg/kg coal with a steam consumption rate 0.2 kg/kg coal, while the quality of the generator

gas remains high (7% non-combustible species), the calorific value increases to 19.7 MJ/m^3, and the gas temperature decreases to 187°C. The generator gas produced by steam-oxygen gasification can be recommended for combustion in OFCs.

7. Carbon dioxide-oxygen gasification should be considered as an alternative to steam-oxygen gasification, since CO_2, unlike steam, does not need to be generated, as it is a by-product of the coal-fired power plant. Mixing carbon dioxide with oxygen allows to reduce oxygen consumption rate to 0.42 kg/kg coal with a carbon dioxide consumption rate 0.3 kg/kg coal, while the quality of the generator gas (2.9% non-combustible species) and the calorific value (17.2 MJ/m^3) remain almost the same, while the gas temperature decreases to 260 °C (higher than with steam-oxygen blowing). The gasification quality is somewhat worse than with steam-oxygen blowing, but steam generation is not required. A comparison of steam-oxygen and oxygen-carbon dioxide blowing for coal-gasified oxy-fuel power plants should be made through cycle modeling.

Also, a separate thorough investigation of pure CO_2 as a blowing agent is required.

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Conflict of interest

The authors declare no conflict of interest

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